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THE THERMAL CONDUCTIVITY OF LEAD.

BY F. L. BISHOP.

Presented by F. A. Laws, December 13, 1905. Received January 12, 1906.

THE method of determining the thermal conductivity here employed is the modification of the wall method due to Professor F. A. Laws, and the object of this research is to determine the limits of accuracy of that method.

For a general discussion of the method the reader is referred to the article, "A Method of Determining Thermal Conductivity," by F. A. Laws[1] with F. L. Bishop and P. McJunkin. A part of the apparatus used in this investigation is the same as that used in the previous one.

GENERAL DESCRIPTION OF APPARATUS.

A diagram of the apparatus is shown in Figure 1. The shell A is supported at the centre of a large tank filled with oil and can be maintained at any desired temperature. The nickel wires from the two surfaces of the shell are led to the mercury cups a, b, in the box C. A piece of the original lead L is brought from the shell to one of the calibrating tanks D. To this lead wire is electroplated a nickel wire similar to the wires on the sphere; consequently at T we have a junction exactly similar to the junctions on the shell. The wire is brought to the mercury cup c in the box C. This provides a means of determining with the required degree of accuracy the exact temperature of the outside or inside of the shell.

The wires from the galvanometer G are fastened to the block E, which can be placed in position in the mercury cups a, b, and thus connect the galvanometer with the thermo-electric junction on the shell. The deflection of the galvanometer G was calibrated by connecting the terminals E at M with the fall of potential across the standard ohm R_4, this fall of potential being compared with the Carhart-Clark cell H by means of the resistances R_1 and R_2.

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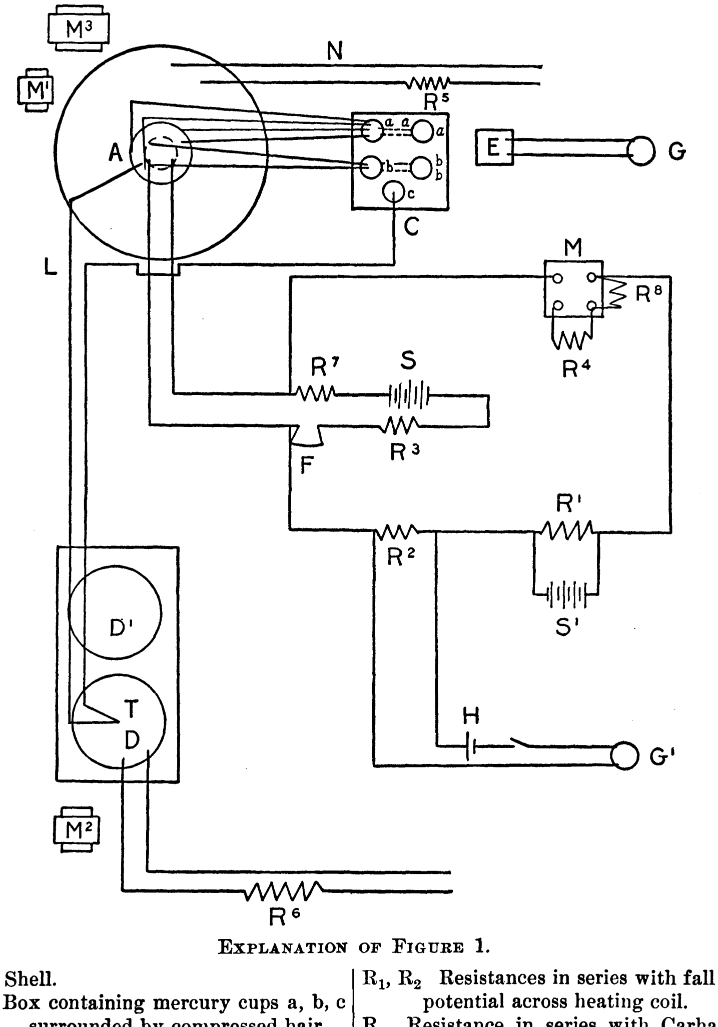
[1] These Proceedings, 1906.



Explanation of Figure 1.

A	Shell.
C	Box containing mercury cups a, b, c surrounded by compressed hair.
D, D_1	Calibrating tanks.
E	Block containing terminals of galvanometer.
F	Ammeter.
G, G_1	Galvanometers.
H	Carhart-Clark cell.
M	Mercury cup containing terminals of standard ohm.
N	220 volt mains.
M_1, M_2, M_3	Electric motors.
R_1, R_2	Resistances in series with fall of potential across heating coil.
R_2	Resistance in series with Carhart-Clark cell.
R_3	0.1 ohm in series with ammeter.
R_4	Standard ohm.
R_5, R_6, R_7	Adjustable resistances.
R_8	Resistance in series with galvanometer to counterbalance resistance of nickel leads.
S, S_1	Storage cells.
T	Nickel-lead junction.

The heat for the inside of the shell is furnished by the storage cells S. This current is measured by the ammeter F, and the fall of potential is balanced against the Carhart-Clark cell H by means of the resistances R_1 and R_2 and the galvanometer G_1. A resistance R_3 of 0.1 ohm connected in series with the ammeter provides a means of calibrating the ammeter in position and during readings. The fall of potential at R_3 was balanced against that of R_1 in series with the storage cells S_1, this being balanced just before and after against the Carhart-Clark cell H.

M_1, M_2, M_3 are electric motors for agitating the oil outside the shell, inside the shell, and around the junction T respectively.

The current from the 220 power mains N furnished heat to the oil outside the shell, while the current from the 110 mains maintained the tank D at constant temperature.

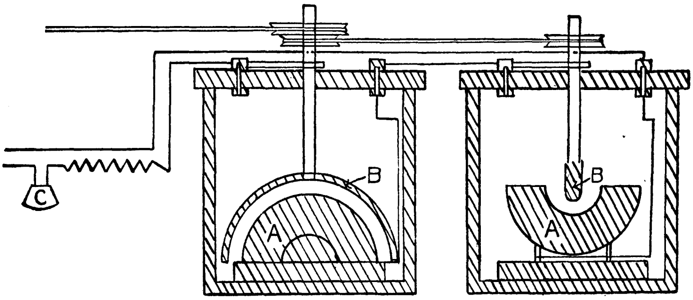


FIGURE 2.

DETAILS OF APPARATUS.

1. *Shell.*

The shell is in the form of a hollow sphere of cast lead, in the casting of which every precaution was taken to have the lead free from blowholes and of uniform quality. It is divided into two hemispheres by a plane passing through a great circle of the sphere. A radial hole was provided for the admission of wires to the heating coil, thermo-electric junctions, and also for the shaft to drive the fans on the interior of the sphere.

The shell was coated by electrolysis with nickel of a uniform thickness of about .7 mm. The apparatus as arranged for this is shown in Figure 2. The solution used was nickel-ammonium sulphate made slightly acid with citric acid.

The nickel wires, six in number, two inside and four outside, were electroplated to the nickel. The two from the inside were brought through a fire-clay plug which would completely insulate them.

2. *Source of Heat.*

The heat is supplied to the interior of the shell by means of an electric heating coil (Figure 3) consisting of German-silver wire. Copper wires were soldered to these, which were taken out of the shell through the fire-clay plug. The oil in the cavity was agitated by two sets of fans soldered to a shaft of steel .7 mm. in diameter. This extended out through the fire-clay plug. A pulley on this shaft was connected by a belt to the small motor M_1. The fans were about 3 cm. in diameter, and so arranged that the oil would circulate towards the centre of the cavity or away, according to the direction of rotation of the fans.

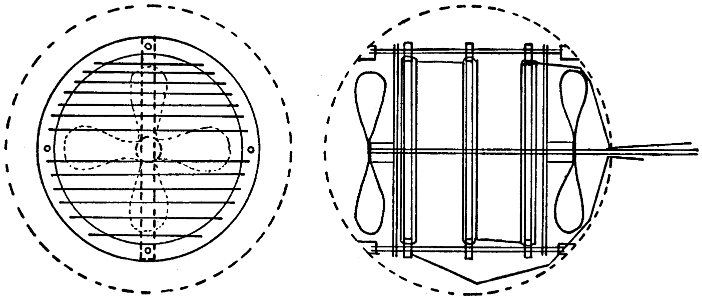


FIGURE 3.

A battery of storage cells supplied the necessary current at a constant pressure.

3. *Constant Temperature Bath.*

For the details of the constant temperature tank see previous article.

DATA.

1. *Constant Data.*

The following are the dimensions of the sphere:

External radius . . .	8.742 cm. ± .00055 cm.
Internal radius . . .	3.695 cm.
Thickness	5.045 cm.

2. *Experimental Data.*

Procedure. — The general method of procedure in taking a set of readings was to adjust the temperature of the large tank to approximately the temperature at which it was desired to take readings. Then the fans in the cavity of the shell were set in rotation and the current from the storage cells turned into the heating coil. The temperature of the outside was adjusted until it remained constant, then the apparatus was allowed to run constant for approximately two hours, tests being made from time to time to determine when it had become constant. The deflection of the galvanometer was read every two minutes. The ammeter reading was maintained constant by an adjustable resistance which would permit of a very small change in the current. The fall of potential across the heating coil was balanced against the Carhart-Clark cell several times during a run, which was usually thirty-two minutes. The variation in the temperature of the oil surrounding the shell was taken at frequent intervals. The galvanometer was immediately calibrated after the readings had been taken.

Readings. — The following set of readings illustrates the constancy of the various quantities. The first column gives the actual readings on the galvanometer, the second gives the difference between each two successive readings, i. e. the double deflection, the third and fourth give the current and the ratio from which to determine the voltage. The column marked "Temperature Tank" gives the variation of the temperature with time of the oil surrounding the shell.

THERMAL CONDUCTIVITY. MARCH 16, 1905.

Readings.	2 D.	Amperes.	Volts.
98.15	. .	4.500	209177
5.80	92.35		9177
98.40	92.60		Ohm at 21°.5 C.
6.00	92.40		C.-C. cell at 21°.6 C.
98.35	92.35		
5.85	92.50		
98.30	92.55		
5.95	92.35		
98.25	92.30		
5.85	92.40		
Mean,	92.433 ± 0.024		

Galvanometer Calibration.		Temperature Tank.
98.20	. .	5.203 at 11:03
6.30	91.90	5.202 at 11:08
98.23	91.93	5.200 at 11:16
6.22	92.01	5.199 at 11:28
98.23	92.01	
6.19	92.04	Tank at 92°.4 C.
98.19	92.00	Inside at 101°.7 C.
Mean,	91.982 ± 0.014	Mean at 97°.8 C.

R = 190000 in series with storage cell and ohm.
Ratio to balance Clark cell against storage cell:
209177
9177

THERMAL CONDUCTIVITY. MARCH 18, 1905.

Readings.	2 D.	Amperes.	Volts.
12.65	. .	4.500	209180
91.90	79.25		9180
12.65	79.25		Ohm at 27°.7 C.
92.15	79.50		C.-C. cell at 22°.5 C.
12.65	79.50		
92.10	79.45		
12.65	79.45		
92.00	79.45		
Mean,	79.407 ± .070		

Galvanometer Calibration.		Temperature Tank.
91.10	. .	3.190 at 1 : 44
13.80	77.30	3.189 at 1 : 50
91.10	77.30	3.180 at 1 : 57
13.85	77.25	3.180 at 2 : 11
91.10	77.25	
13.85	77.25	
Mean,	77.270 ± .020	

R = 220000		Tank at 48°.5 C.
Ratio: 209183		Outside at 53°.2 C.
9183	C.-C. cell at 22°.7 C.	Mean, 56°.7 C.

MEANS OF DIFFERENT SETS OF READINGS.

Date.	2 D.	Amperes.	Volts.	Temperature.	Thermo E. M. F.
March 16	92.42	4.570	32.82	97°.8	173.20 M. V.
" 18	79.41	4.570	32.75	56°.7	153.01
" 21	63.08	4.570	21.94	102°.5	117.52
" 22	58.22	4.570	22.36	77°.6	111.76
" 23	54.40	4.570	21.01	71°.2	101.07
" 24	65.10	5.079	23.93	58°.0	126.29
April 3	29.95	5.079	13.04	21°.9	60.77
" 4	29.65	5.087	13.02	22°.7	60.40

THERMO-ELECTROMOTIVE FORCE.

The thermo-electromotive force per degree was determined by placing the hemispheres in two adjacent tanks, connecting them with a piece of the original lead, and maintaining these tanks at a constant difference of temperature, this difference of temperature being measured by means of two Beckman thermometers, one of them being a standard. The electromotive force thus produced was measured by noting the double deflection on a galvanometer and then calibrating this galvanometer deflection against a known electromotive force.

Apparatus (Figure 4). — This apparatus consists of two cylindrical sheet iron tanks, each 35 centimeters in diameter and 45 centimeters deep, packed in a wooden box 45 × 50 × 100 centimeters. One hemisphere was suspended on a wooden frame at the centre of each tank. A fan at the bottom of each tank, which could be rotated in either direction, and driven at various speeds by means of an electric motor, served to keep the oil in the tanks in motion.

The frames supporting the hemispheres extended into the tanks about 3 cm., thus preventing the oil from taking up a regular rotary motion. These frames also served to hold the wires of the heating coil, by means of which the temperature of the tanks could be raised. With a bank of lamps and an adjustable resistance in series with the coils, the tanks could be maintained at any desired temperature above that of the room.

The two hemispheres were joined by a piece of the same lead as the spheres. In order to insure perfect electrical contact, a small hole about 0.1 cm. in diameter was drilled into each hemisphere, to a depth of about 0.5 cm., and the end of the lead wire was carefully scraped and forced into this hole with a wooden wedge.

The leads from the nickel were brought to different points on the

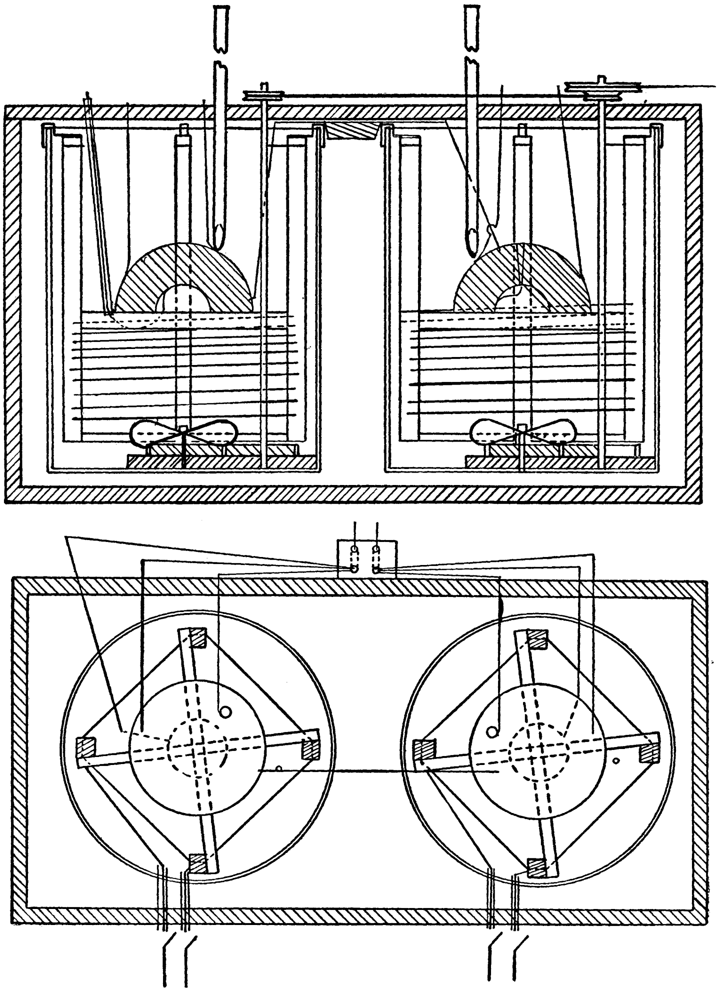


Figure 4.

wooden cover of the box which contained the tanks, the leads from the inside being insulated in glass tubes, so that there would be no chance of their touching the sphere at any point except where they were attached.

These leads were brought to two mercury cups which could be connected directly to the galvanometer.

The Beckman thermometers were so placed that they came in contact with the sphere where the nickel wires were attached.

Procedure. — The temperature of the tanks was adjusted until the difference between them was less than 5° C. The standard Beckman was placed in one tank and Beckman No. 2 in the other. The readings were then taken every two minutes, the galvanometer deflection being taken at the same time. After a series of readings the standard thermometer was transferred to the other tank and placed in contact with the sphere as close to Beckman No. 2 as possible. After an interval of sufficient length to insure the two thermometers being at the same temperature, their readings were taken, the tank meanwhile being maintained as nearly as possible at its original temperature. If this tank has not changed in temperature during the comparison of the thermometers, then the difference in the readings of the standard, after correction for calibration, etc., will give the true difference in temperature of the tanks to 0.001° Centigrade. If, however, the reading of Beckman No. 2 has changed, it will be necessary to add or subtract this reading to the difference of the readings of the standard. The true temperature of one of the tanks was taken by means of an ordinary thermometer reading directly to tenths of a degree Centigrade.

READINGS ON THERMO-ELECTROMOTIVE FORCE.

The following set of readings illustrates the method and constancy of the different readings:

THERMO-ELECTROMOTIVE FORCE. FEBRUARY 20, 1905.

All Junctions.		Tank No. 1 Higher at 51°.4.	
Readings.	2 D.	Standard.	Beckman.
79.18	. .	4.289	3.850
49.31	29.87	4.289	3.851
79.15	29.84	4.289	3.853
49.31	29.84	4.289	3.853
79.18	29.87	4.289	3.854
49.33	29.85	4.291	3.854
79.15	29.82	4.292	3.855
49.32	29.83	4.293	3.855
79.18	29.86	4.294	3.858
49.30	29.88	4.294	3.857
	29.852 ± .005	4.291 ± 0.005	3.854 ± .0004

Galvanometer Calibration.		Comparison.	
50.14	. .	1.659	3.823
79.70	29.56	1.628	3.792
50.12	29.58	1.633	3.797
79.71	29.59	1.633	3.797
50.11	29.60	1.638	3.701
	29.582 ± .0052		

R = 75000 at 21°.1
Ohm, at 21°.0
Clark cell, at 21°.1
Ratio: 77430
27430

Temp. Diff., 2°.6504

E. M. F. per degree, 20.58 M. V.
at 50°.0

MEANS OF READINGS ON THE THERMO-ELECTROMOTIVE FORCE.

Date.	No. of Junction.	2 D.	Diff. of Temp.	Temp.	E. M. F. per degree.
Feb. 7	1 and 4 outside	41.51	4°.318	44°.4	20.56 M. V.
" 7	1 and 3 outside	43.14	4°.366	44°.4	20.57 "
" 20	All	29.85	2°.650	50°.0	20.58 "
" 22	All	35.09	3°.066	76°.5	21.43 "
" 22	1 and 3 outside	32.50	3°.061	76°.5	21.39 "
" 23	All	55.43	4°.814	87.°6	21.81 "

These results are expressed graphically in the following curve (Figure 5).

SOURCES OF ERROR IN CALIBRATING THERMO-ELECTROMOTIVE FORCE.

1. *Difference of temperature.* — The difference of temperature was determined by a Beckman thermometer standardized between 0° and 100° by the Reichstanstalt, to an accuracy of $\frac{1}{1000}$° for a difference of temperature not exceeding 5°. All corrections were applied to the standard.

2. *True temperature.* — An error in this reading of 0°.5 would cause an error of less than $\frac{1}{10}$ of 1 per cent in the value of the electromotive force per degree. The error in the thermometer used for this purpose was much less than this.

3. *Resistance of nickel lead wires.* — This error was large, due to the fact that the galvanometer was connected in series with this resistance when finding the deflection, but when the galvanometer was calibrated the deflection was produced by the difference in potential at the termi-

nals of a standard ohm, consequently the resistance in this case in series with the galvanometer was zero. It therefore became necessary to introduce into the galvanometer circuit when calibrating it a resistance equal to the nickel leads. This was done by means of two mercury cups which were connected by a coil of copper wire, thus eliminating the possibility of any additional thermo-electromotive force. The resistance of the nickel leads was determined to a hundredth of an ohm, it being shown that a change of this amount in the galvanometer circuit produced a negligible change in the deflection.

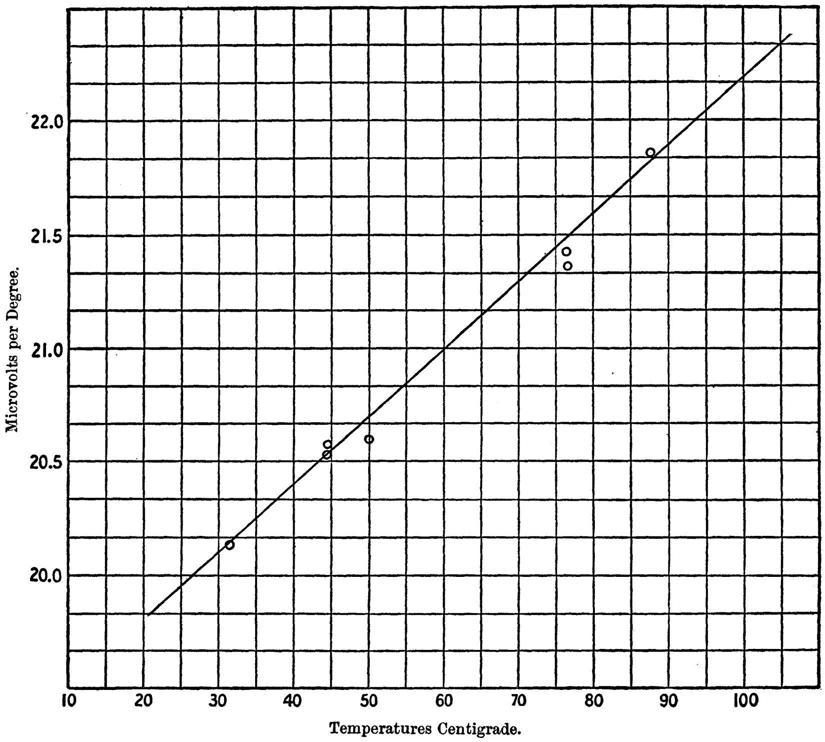


Figure 5.

Diagram of Thermo-Electric Force.

4. *Thomson effect.* — The resultant thermo-electromotive force per degree is the sum of the Seebeck and Thomson effects. It is to be noted that the conditions in determining the electromotive force are almost

exactly identical with the conditions under which the electromotive force is to be employed; as, for instance, the nickel wires will extend in each case from a bath of hot oil to the cold air, and the difference of temperature between the oil and the air at any one particular temperature will be practically identical in the two cases. Again, the nickel wires are to terminate in mercury cups, which will in both cases be at the same temperature with respect to the oil. Also the galvanometer will always be connected to the nickel leads in exactly the same way. Again, the terminals of the nickel wires which dip into the mercury were treated alike in each case, — that is, polished with emery cloth, etc.

5. *Thermo-electromotive forces in the galvanometer circuit.* — Reversed readings were taken which would eliminate any electromotive force in the galvanometer circuit. In order that the galvanometer might be as free as possible from any effects produced by changes in temperature, it was placed in a box 30 × 30 × 46 cm., lined with pressed hair 5 cm. thick; a small opening, covered with glass, gave a view of the mirror. A thermometer was placed inside to determine the changes of temperature. When taking a series of readings under the best conditions this thermometer would indicate no change whatever. The room was maintained at a constant temperature to within 2° C., and during the time necessary for a set of readings the variation in temperature was usually much less than 0°.5.

6. *Electromotive force at the contact of the galvanometer terminals in the mercury cups.* — That an electromotive force of considerable magnitude might exist at this point was discovered by connecting the two mercury cups in which the nickel wires terminated by a single nickel wire, then placing an electric light near the mercury cups; they were heated unequally and a marked deflection of the galvanometer was obtained. While both cups were maintained at the same temperature no deflection was noted, but it is possible that the Thomson effect caused by the wires coming from the air into the mercury would be different unless the mercury cups were maintained at approximately the same temperature for different sets of readings, consequently they were surrounded with compressed hair in a wooden box 25 × 25 × 25 cm., and this was maintained at room temperature. When the room temperature differed greatly from the normal, no attempt was made to take readings.

7. *Resistances.* — All resistances were accurate to .1 of 1 per cent or better. All corrections for changes of temperature, etc., were made.

8. *Standard electromotive force.* — The electromotive force used to calibrate the galvanometer was obtained from a number of storage cells,

connected in series through a resistance, and the drop of potential across this resistance used as the source of electromotive force. This was counterbalanced against a Carhart-Clark cell, which had been recently calibrated.

9. *Sensitiveness of the galvanometer used to balance the electromotive force against the Clark cell.* — This was of sufficient sensitiveness to detect a change of 2 ohms in 10,000 ohms in the Carhart-Clark cell circuit.

10. *Insulation.* — The galvanometer leads were carried through air to the stone pier upon which the galvanometer rested. The leads from the heating coil were brought out through the box in glass tubes. The nickel wires were carefully insulated both inside the tanks and out, and were carefully separated even when entering the mercury cups.

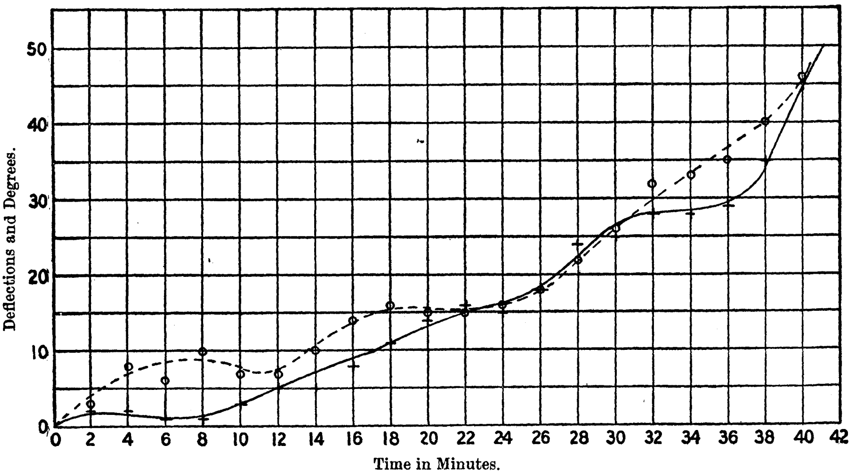


Figure 6.

Comparison of variation (*vide* error 11).

11. *Variation in temperature during a reading.* — Since it was impossible to maintain the tanks at an absolutely constant temperature, it was important to know how closely the galvanometer deflections varied with the variations in the readings of the thermometers. In order to show this, a special set of readings was taken with large variations, and the following plot (Figure 6) shows the results. The results for the plot were obtained by taking the difference in temperature, and the gal-

vanometer reading, subtracting each from the first reading, and plotting this difference as ordinates and the time as abscissa. The two curves thus obtained should be approximately the same if the difference in temperature and galvanometer deflection vary at the same rate.

12. *Variation in difference of temperature during a reading.* — That this variation was less than .1 of 1 per cent is shown by the results.

13. *Change of zero in the galvanometer.* — Double deflections were always used, consequently the zero was not needed.

14. *Different junctions give the same electromotive force.* — See Summary of Results.

15. *A variation in the difference of temperature gives the same result for the electromotive force per degree.* — See Summary of Results.

16. *The resultant electromotive force per degree is the same no matter which tank is at the higher temperature.* — See Summary of Results.

17. *The temperature of the oil not the same as that of the spheres.* — The thermometers were placed in the same relative position in both tanks, and since the tanks were constructed the same, and the oil rotated in the same direction, and the difference in temperature being small, the thermometers would both be at the same relative amount above or below the temperature of the spheres. Placing the thermometers in different parts of the tank gave the same difference.

18. *Variation of rate of agitation of oil.* — The rate and direction of rotation of the oil was changed repeatedly, but no effect could be discovered in the results. The direction of rotation was the same in both tanks, but the rate was sometimes the same and sometimes quite different.

For errors in calibrating galvanometer see errors under conductivity.

19. *Error in Beckman thermometer No.* 2. — When comparing the two thermometers, if the tank has changed in temperature, then it becomes necessary to use the difference of two readings of Beckman No. 2, but as this difference never exceeded a few hundredths of a degree it was assumed that there would be no error.

20. *Error in connecting the two hemispheres.* — It was found in the research on iron by this method that a materially different electromotive force was obtained when the position of the iron connecting the hemispheres was changed. A number of experiments were made to clear this point. It was found that the electromotive force was independent of the method of attaching and position of the connecting wire on the hemispheres as long as the electrical contact was good. This was a simple matter with lead.

Sources of Error in Measuring Conductivity.

1. *Purity of lead.* — The lead was obtained as pure as possible in the granulated form. Every precaution was taken in casting to keep it free from impurities. Clean chips from both parts of the shell gave 99.16 per cent pure. Impurities, iron and aluminium. Density: 11.313 gms. ± 0.018 per c.c. at 22° C.

2. *Blow-holes.* — Probably the most difficult correction to determine was that due to blow-holes. Every precaution was taken in the casting to make it free from blow-holes. In the turning, constant and careful watch failed to show the least trace of blow-holes, although a thickness of about 6 mm. was taken from both inside and outside.

The presence of large blow-holes in either half would show in the weight. A special balance was constructed for this purpose, which was sensitive to 50 mmg. under full load. The weight was found in this way to be: —

Top	14,640.98 gms.
Bottom	14,642.66 gms.
Difference . . .	1.68 gms.

This would indicate that the variation in the amount of lead in the two parts is less than .013 per cent. This, together with the close agreement of the volumes as found by measurement, would indicate the probable absence of large blow-holes.

3. *Variation of conductivity due to the two halves not being close together.* — That this is negligible is shown as follows: The surface of the cavity from which heat is conducted equals 172 cm^2. If the two parts are separated by a non-conducting space of .1 mm., the amount of surface in the cavity would be decreased by only .2 cm^2. The surfaces fitted so well that it was practically impossible to slide one over the other. In order to be certain that no oil flowed in or out, the outside junction of the two hemispheres was sealed with shellac.

4. *Conduction through hole carrying shaft and wires.* — This hole at the surface of the cavity was 4.8 mm. in diameter. If this hole was filled with a non-conducting material the error would amount to less than .2 per cent. But the hole was partly filled with copper, nickel, and steel, all of which have a greater conductivity than lead, and partly by fire-clay, which has a smaller conductivity than lead. These would tend to neutralize each other and make this error negligible.

5. *Variation in source of energy.* — The energy was supplied from a battery of storage cells. A rheostat with a very fine adjustment was connected in series, so that any change might be counterbalanced. Adjustment of this rheostat was made every minute if there was any change in the current. In this way the movement of the needle of the ammeter was less than one twentieth of a division.

6. *Energy supplied by agitating fans in the cavity.* — These fans rotated about 800 times per minute. The energy supplied was determined by placing the coil with fans in a calorimeter containing oil, rotating the fans at the required rate, and determining the rate of increase of temperature not exceeding 1° C. Energy was then supplied to the coil until the rate of increase was approximately double.

Three determinations resulted as follows:

0.366 watts
0.344
0.385
Mean, 0.365 ± 0.10.

Since the total energy supplied was about 100 watts, this correction was determined with sufficient accuracy.

7. *Correction on dimensions of shell.* — The shell was measured by a special micrometer caliper made by Brown and Sharpe for this work. This was compared with a standard meter, which was compared by the Société Genevoise with their standard.

8. *Variation in the thickness of the nickel.* — When the nickel was being plated to the lead it was first plated on the outside, frequent measurements being taken to insure its being of a uniform thickness, the electrodes being adjusted when it was necessary to increase the thickness at any particular place.

During the plating of the inside, measurements were taken in the same way, so that the thickness of the nickel probably does not vary over 0.2 mm. However, in the manipulation of the hemispheres small portions of the nickel cracked off, from the outside near the edge of the hemispheres. The amount cracked off in this way is approximately 5 sq. cm., the largest amount in one place being perhaps 2 sq. cm.

9. *Conduction of the heat from the shell at the points where the nickel wires were electroplated.* — In electroplating the wires to the shell the nickel on the shell was filed slightly and a small depression made in which to put the wire. After plating over the wire, the thickness of the

nickel at this point varied little from that at any point. The wires were 0.3 mm. in diameter.

10. *Change in temperature in the oil surrounding the shell.* — It was impossible to maintain this oil at exactly a certain temperature. The temperature was therefore allowed to vary, part of the time increasing and part of the time decreasing, and by the same amount both times. This total change did not exceed a few hundredths of a degree. See Readings.

11. *Variation in the agitation.* — The fan for agitating the oil on the outside of the shell was always driven in the same direction, as it was evident from the motion of the oil that this direction gave much better agitation close to the shell.

On the inside of the shell the fans were usually driven in the same direction, and always at the same speed, but a change in the direction did not appear to produce any change in the deflection. It would appear from a consideration of the construction of the heating coil that a change in the direction of rotation inside the cavity should produce a change in the galvanometer deflection. That it did not may be due to the position selected at which to attach the nickel wires on the inside.

12. *Amount of oil in the cavity.* — The fire-clay plug had two holes by which oil could enter or air leave when the shell was immersed in oil. At first the shell was immersed in oil and the air exhausted from over it by means of a pump, but it was found that this was an unnecessary precaution. A small wedge which could be easily withdrawn was placed between the two hemispheres, thus allowing the air and oil to enter the cavity at the separation of the spheres, and also through the fire-clay plug. The oil was agitated in the cavity and at the same time heated to expel the air. The wedge was withdrawn and the holes in the fire-clay plug sealed with shellac.

13. *Calibration of the ammeter.* — The ammeter read from zero to 5 amperes, the smallest division being 0.05 of an ampere. The resistance of the tenth of an ohm in series with the ammeter was accurate to $\frac{1}{50}$ of 1 per cent. The drop of potential across its terminals could be balanced against the Carhart-Clark cell to an accuracy of 0.1 per cent. Consequently it was possible to determine the current to within 0.1 per cent.

14. *Determination of voltage.* — This was balanced directly against the Carhart-Clark cell, and the galvanometer was sensitive to better than 0.1 of 1 per cent.

SUMMATION OF RESULTS.

Date		Temp.	Diff. T.	C. V.	K
March	16	97.8	7.844	149.97	.05673
"	18	56.8	7.321	149.68	.06067
"	22	77.6	5.198	102.17	.05832
"	23	68.0	4.763	96.03	.05980
"	21	102.5	5.289	100.26	.05645
"	24	58.0	6.034	121.56	.05978
April	3	21.9	3.057	66.24	.06429
"	4	22.7	3.034	66.21	.06475

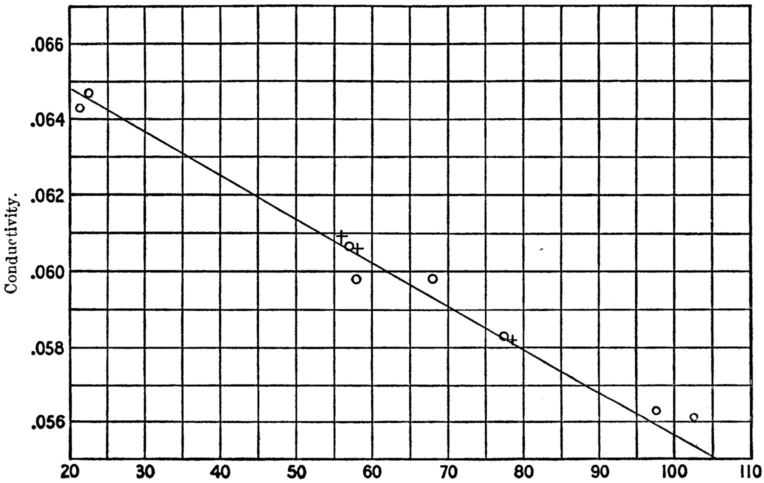


FIGURE 7.

$K_t = 0.0645\,[1 - 0.00159\,(t - 20)]$.

Note: Results marked + are preliminary.

DISCUSSION OF RESULTS.

From the plot of the value of K we find the average deviation of the results to be less than 0.15 per cent, — the maximum variation being a little over 1 per cent. The coefficient $= \dfrac{K_{100} - K_{20}}{80\,K_{20}}$ as obtained from these results is found to be 0.00159.

A point to be noticed is that the amount of energy supplied to the interior of the shell as represented by the watts was never the same, and varied from 66.21 to 149.97; and again, the difference in temperature varied from 3°.034 C. to 7°.844 C.; consequently we would conclude that the method within these limits is independent of the total energy supplied to the inside, and to the difference in temperature. Three different forms of heating coil being used would indicate that the method was independent of the form of the coil. Another point to be noticed is that four preliminary results, taken when the apparatus was set up in the laboratory at Bradley Institute, agree better than 0.5 per cent with the results obtained with the apparatus used in the Ryerson Laboratory. This would imply that the results here obtained are independent of all the electrical apparatus employed. The results for the thermo-electromotive forces give values and slope of the curve, which are almost identical with the ordinary values given for pure lead and pure nickel. Since the thermo-electromotive force between lead and nickel has been frequently determined and with a high degree of accuracy, we may infer that the results here obtained for the thermo-electromotive force contain no constant error, and as shown by the data are probably accurate to 0.1 per cent. From which we may infer that the error in measuring the electromotive force when determining the thermal conductivity is also accurate to 0.1 per cent.

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Physical Laboratory, Bradley Institute,
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